Possible Production of the Sigma Meson in Nuclei [*]

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ABSTRACT

It should be a typical subject in this workshop to explore possible change of hadron properties in association with that of QCD vacuum due to an environmental change. In this report, we first summarize what hadrons are expected to show such a change and how they do. Then we propose several experiments including the ones utilizing electron and photon beams for examining possible restoration of chiral symmetry in nuclei and the possible existence of the sigma meson. The experiments are based on the observation that the sigma meson may decrease the mass and the width along with the partial restoration of chiral symmetry in the medium.

1. Introduction

An underlying observation for this workshop on "Quark Nuclear Physics" can be the following[3]: (1) The QCD vacuum will change under an environmental change, characterized by the baryonic density ρ_B, temperature T, external gauge fields such as magnetic field $\vec{B}$. (2) According to a general principle of the quantum field theory, a change of the vacuum may reflect in those of the elementary excitations, hadrons for the QCD vacuum. A nucleus is of course a typical system with ρ_B.

The QCD vacuum is characterized by the confinement of the colored objects, dynamical breaking of chiral symmetry, $U_A(1)$ anomaly and so on. The rules extracted from hadron phenomenology such as the vector-meson dominance (VMD) and the Okubo-Zweig-Iizuka (OZI) rule might be also related with some fundamental properties of the QCD vacuum.

The problems are then what hadrons change the properties, and how they do in hot and/or dense medium. One should also ask how they are detected in experiment. Such a theoretical study was initiated about a decade ago by several authors independently[4,5]; see [3] for a review. In Table 1, we list up several hadrons and their expected behaviors as the fundamental properties of the QCD vacuum change[3]. In association with (partial) restoration of chiral symmetry, the mass of the σ meson[6,7] is expected to decrease. Some people[8] expect that the vector mesons ρ, ω and ϕ also show a decrease of their masses in association with the chiral restoration.[a] The $U_A(1)$ anomaly, which is responsible for lifting the η' meson mass as high as about 1 GeV and make the $\eta'(\eta)$ almost flavor singlet (octet), may be cured at high temperature. This may manifest itself as the decrease of the mass $m_{\eta'}$,[10] for example. The de-

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[*]The major part of this report is based on [1] and a part of [2].

[a]However see also [9]. The vector meson dominance (VMD) principle might be or might not be modified at $T \neq 0$ and/or $\rho \neq 0$.[9] This is related with the behavior of the vector mesons in hot and/or dense medium.

confinement will be better reflected in the properties of heavy-quark systems such as J/ψ[11] than in light hadrons. In this talk, we emphasize the significance of the sigma meson in QCD[3,2], and propose several experiments to produce the σ in nuclei [12,1,2] for confirming the existence of the elusive particle and examining the possible change of properties of the meson due to a partial restoration of chiral symmetry in baryonic medium.

Physics	Phenomena	Observables	Expectations
Chiral Restoration	Decrease of m_σ	2γ, 2π from σ	A bump in the low mass region
	Decrease of m_ρ, m_ω	dileptons from ρ, ω	Shift or smearing of the peak
	Decrease of m_ϕ	K^+K^- and dileptons from ϕ	Reduction of the K^+K^- yield
$U_A(1)$-Restoration	Decrease of $m_{\eta'}$	2γ from η'	Decrease of the invariant mass
	Change of the mixing property	The branching ratio of η and η' from J/ψ	Increase of the mixing angle θ_η
Decon-finemnet	Decrease of $m_{J/\psi}$	dileptons from J/ψ	Decrease of the invariant mass

Table 1. Interesting observables and their expected behavior in relation with the chiral transition,the possible restoration of the $U_A(1)$-symmetry and partial deconfinement at finite temperature and/or density. See the review [3] for the relevant references.

2. The Sigma Meson

The sigma meson is the chiral partner of the pion for the $SU_L(2) \otimes SU_R(2)$ chiral symmetry in QCD: In the $(1/2, 1/2)$-representation, the sigma field σ constitutes the quartet together with the three pion fields. The order parameter of the chiral transition of QCD is the scalar quark condensate $\langle \bar{q}q \rangle \sim \sigma$, and the vacuum is determined as the sate where the effective potential $\mathcal{V}(\sigma)$ takes the minimum. Let us denote the minimum point by σ_0. Then the particle representing the quantum fluctuation $\tilde{\sigma} \sim \langle : (\bar{q}q)^2 : \rangle$ is the sigma meson. ($\sigma = \sigma_0 + \tilde{\sigma}$). In this sense, the sigma meson is analogous to the Higgs particle in the Weinberg-Salam theory as has been emphasized by the present author[13,3,2].

In the ladder QCD[14] and the Nambu-Jona-Lasinio model [15] as a low-energy effective theory[3], the sigma meson has the mass m_σ almost twice of the constituent quark mass ~ 350 MeV, hence $m_\sigma \sim 700$ MeV. Such a scalar meson with a low mass can account for various hadron phenomena[2] including the $\Delta I = 1/2$ rule for the decay process $K^0 \to \pi^+\pi^-$ or $\pi^0\pi^0$ [16], the state-independent attraction in the intermediate

range in nuclear force[17], quark contents of the nucleon in the scalar channel and the π-N sigma term $\Sigma_{\pi N}$[3] and so on; a nice summary is given in [2] for the significance of the sigma meson in nuclear and hadron physics.

Experimentally, there is, however, a controversy on the identification of the nonet scalar mesons in the particle zoo, and some people are skeptical even about the existence of the sigma meson with a rather low mass, say about 600 to 800 MeV. Such skepticism may be attributed to the facts that the decay of the sigma meson to two pions gives rise to a huge width $\Gamma = 400 \sim 1000$ MeV of the sigma meson, and that a possible coupling with glue balls with $J^{PC} = 0^{++}$ make the situation obscure. Therefore it is remarkable that recent extensive works on the phase shift analysis of the π-π scattering in the scalar channel claims a pole of the scattering matrix in the complex energy plane with the real part Re $m_\sigma = 500 - 700$ MeV and the imaginary part Im$m_\sigma \simeq 500 - 800$MeV.[18] There is also preliminary experimental result at KEK[19], which seems to show a bump around 600 MeV with a width ~ 400 MeV in the reaction $\pi^- p \rightarrow n\pi^0\pi^0$. The 2 π^0 are detected by 4 γ's. This is a clever experiment in the sense that by confining to the $2\pi^0$ channel, one can reject the iso-vector channel where we would have a huge yield from the rho meson.

3. The Sigma Meson at $T \neq 0$ and/or $\rho_B \neq 0$

Effective theories of QCD[3] show that the sigma meson mass m_σ decreases in association with the chiral restoration in hot and/or dense medium, while the pion mass keeps its value in free space as long as the system is in the Nambu-Goldstone phase. Then the width of the σ is also expected to decrease due to the depletion of the phase space for the decay $\sigma \rightarrow 2\pi$. Thus one can expect a better chance to see the sigma meson in a clearer way in hot and/or dense medium than in the vacuum. Actually, the decrease of the mass is already considerable even in the nuclear density ρ_0, as shown in [7].

It is worth mentioning that the Walecka model[20] also predicts the decrease of the masses of the scalar meson as well as the ω meson in hot and/or dense nuclear matter: Saito, Maruyama and Soutome (SMS)[20] showed that the extent of the decrease of m_σ at ρ_0 reaches as large as 20% of that in the free space, even at zero temperature. It should be mentioned here that there are attempts to "derive" the Walecka model in a context of chiral symmetry, although the original Walecka model is not constructed to have chiral symmetry; see [21] and references cited therein. SMS showed that it is crucial to include the effects of the Dirac sea of nucleons for obtaining the decrease of the meson masses. This is in accordance with the fact that the decrease of m_σ is associated with a change in the vacuum structure, i.e., the chiral restoration, in the chiral models. As is well known, there arises a σ-ω mixing for finite three momentum $\mathbf{q}$ in nuclear matter, which effect is included in SMS's calculation[20]. It should be emphasized that the scalar-vector mixing with finite density is a general feature not

restricted to the Walecka model[22]. This enables us to create our sigma meson by photons in nuclei[12,2]; see below. SMS calculated the dispersion relations $\omega_\alpha = \omega_\alpha(q)$ ($\alpha = \sigma, \omega$) for the sigma and omega mesons in nuclear matter; see Fig. 1. A remarkable point is that $\omega_\sigma(q)$ is almost overlap with the photon line $\omega_\gamma = q$ between $q_1 \simeq 200$ MeV/c and $q_2 \simeq 600$ MeV/c where ω_σ cuts the photon line, i.e., $\omega_\sigma = q$. This means that real photons also can create the σ in nuclei provided that the scalar meson in the Walecka model can be identified with the σ meson relevant with chiral symmetry.

Figure 1

The solid lines show the dispersion relation of the sigma meson (S) $\omega_\sigma(q)$, the longitudinal(L) and the transverse(T) mode of the omega meson at the nuclear density ρ_0 at $T = 0$; taken and modified from a figure by Saito et al[20]. The photon line $\omega = q$ is also shown. The dashed lines show the dispersion relation at $T \neq 0$.

4. Production Mechanism of the Sigma Meson

As we have seen in the last section, the sigma meson may decrease the mass in nuclei, and hence the width due to the depletion of the phase space volume for the decay $\sigma \rightarrow \pi\pi$. Thus we propose several types of experiment[2] to produce the sigma meson in nuclei: one uses pions, another protons and light nuclei and the other electrons (and real photons). To detect the sigma, one may use 4 γ's and/or two leptons. The latter process is possible because a scalar particle can be converted to a vector particle because of the scalar-vector mixing in the system with a finite baryonic density. This mixing is well known in the Walecka model as mentioned above. Microscopically, the process is described by $\sigma \rightarrow N\bar{N}(p-h) \rightarrow \gamma$, where p-h represents nucleon particle-hole excitations. Here σ may be replaced by any scalar particle, and γ any vector particle with the same quantum numbers other than spin and parity.

1. A $(\pi, 4\gamma$ N) A′

In this reaction, the charged pion $(\pi^\pm)$ is absorbed by a nucleon in the nucleus, then the nucleon emits the sigma meson, which decays into two pions. To make a veto for the two pions from the rho meson, the produced pions should be neutral ones which decay to four γ 's.

2. A (P, 4γ N) A$'$

The incident proton, deuteron or ^{3}He ... collides with a nucleon in the nucleus, then the incident particle will emit the sigma meson, which decays into two pions. One may detect $4\,\gamma$'s from $2\,\pi^0$. The collision with a nucleon may occur after the emission of the sigma meson; the collision process is needed for energy-momentum matching.

In the detection, one may observe the two leptons from the process $\sigma \to N\bar{N}(p-h) \to \gamma$ mentioned above: This detection may gives a clean data, but the yield might be small.

3. A (e$^-$, 4γ e$^-$) A$'$

The final example uses the electron beam: The γ ray emitted from the electron is converted to the omega meson in accord with the vector meson dominance principle. The omega meson may decay into the sigma meson in the baryonic medium via the process $\omega \to N\,\bar{N}(p-h) \to \sigma$. The sigma will decay into two pions. One may detect the 4γ's from the 2 neutral pions. As noted in the previous section, real photons may be used to create σ meson for some kinematical region, say $q = 400 - 700$ MeV/c.

5. Brief Summary

We have summarized some phenomena and experiments which are to be pursued in the project of "Quark Nuclear Physics". We have emphasized the importance to catch the tail of the elusive sigma meson somehow. Although it might be hesitating to dare to perform an experiment for possible production of such an elusive particle, one may have a good chance to see a clear signal for the particle in the baryonic medium, because the sigma meson may become rather sharp in nuclei in association with partial restoration of the chiral symmetry. We have proposed several experiments to produce the σ meson in nuclei: Some of them is based on the large scalar-vector mixing at ρ_B for $\vec{q} \neq 0$. The detection should be done by observing neutral pions $(2\pi^0)$.

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